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Water Quality Characteristics of Honokohau Harbor: A Subtropical Embayment Affected by Groundwater Intrusion[1]

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ABSTRACT: This study describes the water quality characteristics of a subtropical embayment that is markedly affected by the infiltration of cold, nutrient-rich groundwater. The spatial, vertical, and tidal variations of physicochemical characteristics (e.g., temperature, salinity, oxygen, turbidity) and nutrients (e.g., nitrate, phosphate, ammonium) are depicted and show conditions of pronounced stratification. The harbor supports an unusual two-layered structure of cold, brackish, nutrient-rich waters overlying a warm, low-nutrient, oceanic layer. Temperature and salinity range from 20.5 to 24.5°C and from 18.1 to 35‰ at the surface and bottom (5.5 m), respectively. High nutrient levels in the surface layer (about 30 μg-atoms NO_3^-/liter and 2 μg-atoms PO_4^{3-}/liter and the close correlation with thermohaline parameters identify groundwater intrusion as the major nutrient source.

The prolific (1.5–2 million gallons per day) and continual groundwater influx produces persistent flow out of the harbor irrespective of the tidal condition and produces harbor flushing rates six to ten times those calculated for tidal flushing alone. The potential eutrophying effects of the groundwater nutrients are avoided as a result of the rapid harbor flushing. This study details the potential impact of groundwater nutrients on the aesthetic and water quality character of island coastal developments, indicates that consideration of terrestrial features (e.g., land slope, rainfall) cannot be used to predict the likelihood or extent of groundwater effects, and describes the importance of infrastructure design to optimize flushing as a critical criterion in maintaining good water quality in such embayments.

THE HONOKOHAU SMALL BOAT HARBOR was created in 1970 by blasting and excavation of approximately 10 acres of shoreline in Honokohau Bay to provide a haven and launch site for boating activities in the area. The resulting origination of pelagic and benthic marine habitats offered a unique opportunity to investigate resulting trends in water quality conditions and to study the seral stages of community succession in this subtropical coastal environment. In addition to delineating valuable ecological cycles regarding succession on substrate that had never before been colonized, the study describes several important phenomena that may influence to some degree the marine character of other coastal developments of this sort in the islands. The harbor's isolation from other affecting forces, such as run-off, river/stream, or domestic/industrial sewage inputs, enhances the predictive value of witnessed trends for other comparable coastal situations.

The purposes of this research, spanning 5 years of investigation, were to monitor community development within the newly created basin, to determine resulting water quality conditions, to use this information to predict the impact of harbor completion (via fivefold expansion of water area), and to direct such expansion so as to minimize

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adverse impact on the harbor and adjacent areas. The associated publications constitute a compendium describing the system's baseline chemical and physical parameters; circulation and flushing patterns; planktonic productivity and/or standing stocks; and the colonization and successional development of fish, coral, mollusk, and echinoderm communities inhabiting this new environment.

The harbor is situated midway between the Ke-ahole airport and Kailua-Kona on the southwest (Kona) coast of the island of Hawaii. The surrounding area is rural; no commercial, residential, or industrial developments exist within 2 mi of the harbor. The coastal area is comprised of prehistoric lava flows from Hualalai Volcano; these lavas, predominantly *pahoehoe* with interspersed *a'a*, are characterized as alkaline olivine basalts (Macdonald and Abbott 1970) and are highly porous and permeable. Typically, little soil material exists in the area and, where present, it is of very thin depth, brown to black in color, and has high levels of iron, aluminum, and silica. The land slope near the harbor is about 1 percent, and the entire area is classified as well to excessively drained. The Honokohau Bay shoreline is predominantly rough lava and rocky in appearance, owing to the geologic recency of volcanic activity. Though coral formations exist within the bay, the area does not support a conspicuous reef as such; most of the submarine substrate is basaltic rock with a thin veneer of calcium carbonate cover. Diffuse groundwater discharge along the shore is a characteristic hydrological feature of the area and has been shown to occur around the entire island (Fisher, Davis, and Sonza 1966, Adams and Lepley 1968, Doty 1968, 1969, Cox et al. 1969). Experts feel that a substantial part of the island rainfall discharges perennially at the shore. The sand reservoir of the area is low, and seasonal fluctuations in the amount of beach sand are expected to follow the patterns for the western beaches of other islands (Moberly and Chamberlain 1964), namely winter erosion and summer accretion. Air temperatures in the area normally range from 19 to 28°C, with an annual average of 24°C at sea level. The mean annual rainfall in the area is 20–30 inches. The harbor is exposed to prevailing onshore winds during the day which increase to 8–10 knots in the afternoon.

The purposes of this paper are to describe the water quality conditions prevailing in this environment; to relate these conditions to the salient geological, climatological, and hydrological features of the area; and to present the baseline environmental parameters relevant to the associated studies. Rather than reiterate water quality values from each year's study, the majority of the reported data are taken from the comprehensive 1975 reconnaissance conducted in connection with an Environmental Impact Study for harbor completion.

MATERIALS AND METHODS

Routine chemical sampling was conducted at 0.5, 1.5, and 3.0 m at each of the four intraharbor stations and from 1.5 and 5.0 m at the oceanic station located about 150 m outside the harbor entrance (Figure 1). Morning sampling took place during ebbing tides (0.6 $\pm$ 0.2 ft) and afternoon sampling during flooding tides (-0.2 ± 0.2 ft). Chemistry samples were prefiltered through Whatman GF/C glass fiber filters and frozen pending analysis. Nitrate concentrations were determined by the method of Wood, Armstrong, and Richards (1967); nitrite, phosphate, and ammonium were determined by the methods described in Strickland and Parsons (1972). Vertical profiles of temperature, salinity, and turbidity were taken at 0.25-m intervals at 37 locations (Figure 1) at both high and low tide conditions. Simultaneous determination of these three parameters was made with an Inter-Ocean Model 503D probe connected to a digital data console that recorded the probe signals on magnetic tape and formatted same for later teletype printout. Similar profiling of dissolved oxygen was done with a YSI oxygen probe, but probe malfunction was apparent and it was necessary to redetermine oxygen concentrations via discrete sampling using the Winkler technique. Sediment character was

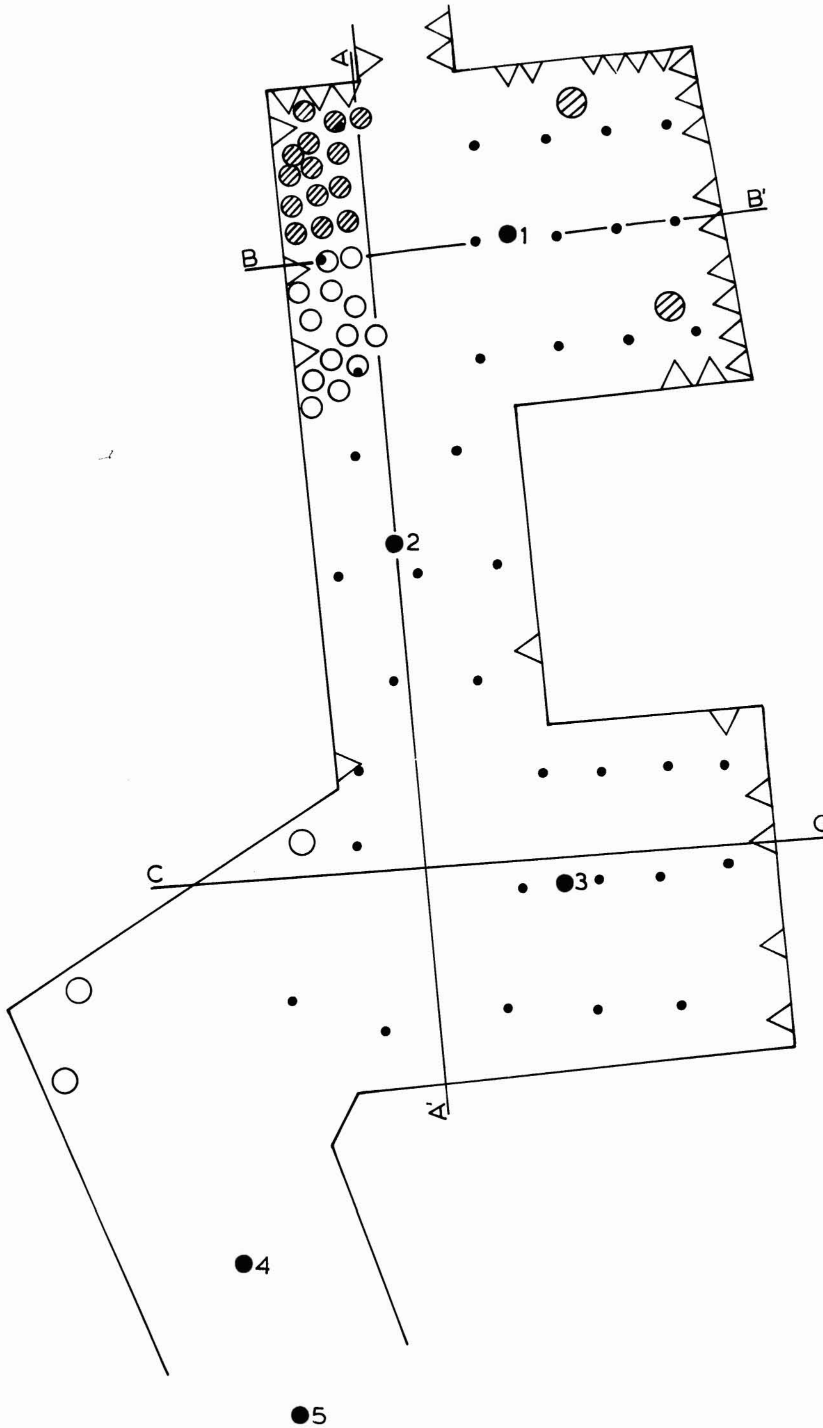

FIGURE 1. Honokohau Harbor sampling sites and groundwater inputs. Large numbered dots represent chemistry sampling stations. Small dots show locations of temperature, salinity, and turbidity profiles. Transect lines indicate harbor cross sections shown in Figures 2 and 3. Triangles and circles represent areas of groundwater intrusion through harbor walls and floor, respectively. Shaded circles indicate areas of maximum groundwater input.

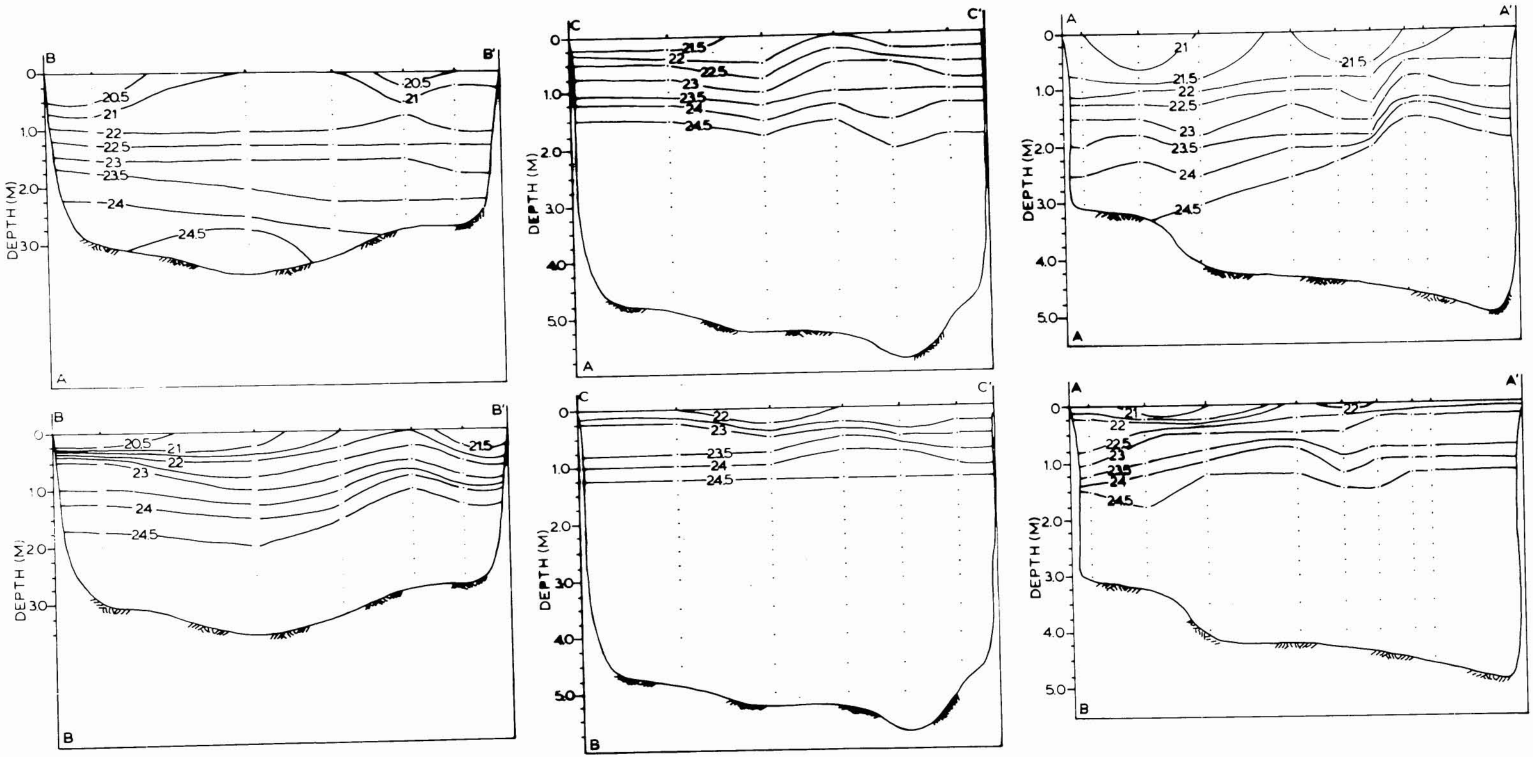

FIGURE 2. Cross sections showing vertical profiles of water temperature in Honokohau Harbor. Axes A–A′, B–B′, and C–C′ describe transects shown in Figure 1. Figures labeled A and B present conditions at low and high tide, respectively.

determined by diver observations and sample collection. Sediment thickness was measured by driving cores into the substrate; 21 sediment samples were collected and analyzed for particle size–frequency distribution by sieving and weighing and for percentage of organic matter by combustion of desiccated samples at 550°C.

RESULTS

Temperature

The temperature results, rounded to the nearest 0.5°C, are presented as harbor cross sections to show the harbor thermal structure and its tidal variation (Figure 2). An outstanding feature of these results is the presence of a cold surface layer lying upon a warm oceanic layer. This condition is maintained by the continuous inflow of cool brackish water through the harbor walls and floor. This groundwater is less dense than the warmer seawater because of its reduced content of dissolved salts. A vertical temperature gradient is thus established between the cool surface waters and the subsurface oceanic waters. The extent of this gradient varies with tidal flow and location within the harbor.

Water temperatures in the back basin range from 20.5°C at the surface to 24.5°C at the bottom (Figure 2, transect B–B′). In the front basin (transect C–C′), the temperature of the surface waters is 21.5–22°C. This 1–1.5°C increase over surface waters of the back basin results from solar heating during passage from the back basin (Figure 2). There is no definable layer of cool unmixed surface water; rather, there exists a continuous gradient of temperature down to the depth of the oceanic layer (24.5°C). Temperature sections of the back basin show that the majority of this basin contains water of suboceanic temperatures at low tide (Figure 2A). The comparatively gradual temperature gradient is maintained by solar heating, mixing, and diffusion processes. Waters of oceanic temperature constitute only a small portion of this basin volume at low tide; however, at high tide the entire basin contains such waters at depths in excess of 1.75 m, and the temperature gradient is considerably more steep (Figure 2B). In the deeper front basin, this gradient is less pronounced and oceanic temperature is attained at 1.5 m. Figure 2 shows that the majority of this basin is oceanic in character at both high and low tides. Ambient ocean temperature is attained at about 1.5 m at low tide, and at high tide this layer extends to about 1.25 m. The east–west harbor transect (A–A′) illustrates the temperature variations of the basins and channel in response to tidal flushing. The temperature gradients are steepest at high tide regardless of location, but the depth at which oceanic temperatures are attained shows greatest variation in the back basin.

Salinity

Salinity shows a distribution similar in several features to that of temperature; namely, a surface layer dominated by groundwater inputs, steep vertical gradients, and a subsurface oceanic layer varying in size in response to tidal conditions (Figure 3). The lowest salinity (18.5‰) was found in the back basin, the area of groundwater input.

The salinity gradient extends virtually to the bottom in the back basin at low tide (Figure 3A). Throughout the harbor this gradient is maintained by advective processes, vertical mixing, and diffusion. The extent of tidal flushing is implied by Figure 3, which shows the variation in the depth of the 35‰ layer in response to the tide. The surface waters of the front basin are about 30‰; this increase over the surface waters of the back basin results from mixing that occurs during its passage from the back basin. The front basin contains undiluted oceanic waters below a depth of 1.75 m at high tide and 2.0 m at low tide. The longitudinal (A–A′) cross section of salinity illustrates the salinity gradient, location of the oceanic layer, and tidal response of each throughout the harbor.

Dissolved Oxygen

Discrete samples were taken from both the surface and subsurface waters of the two

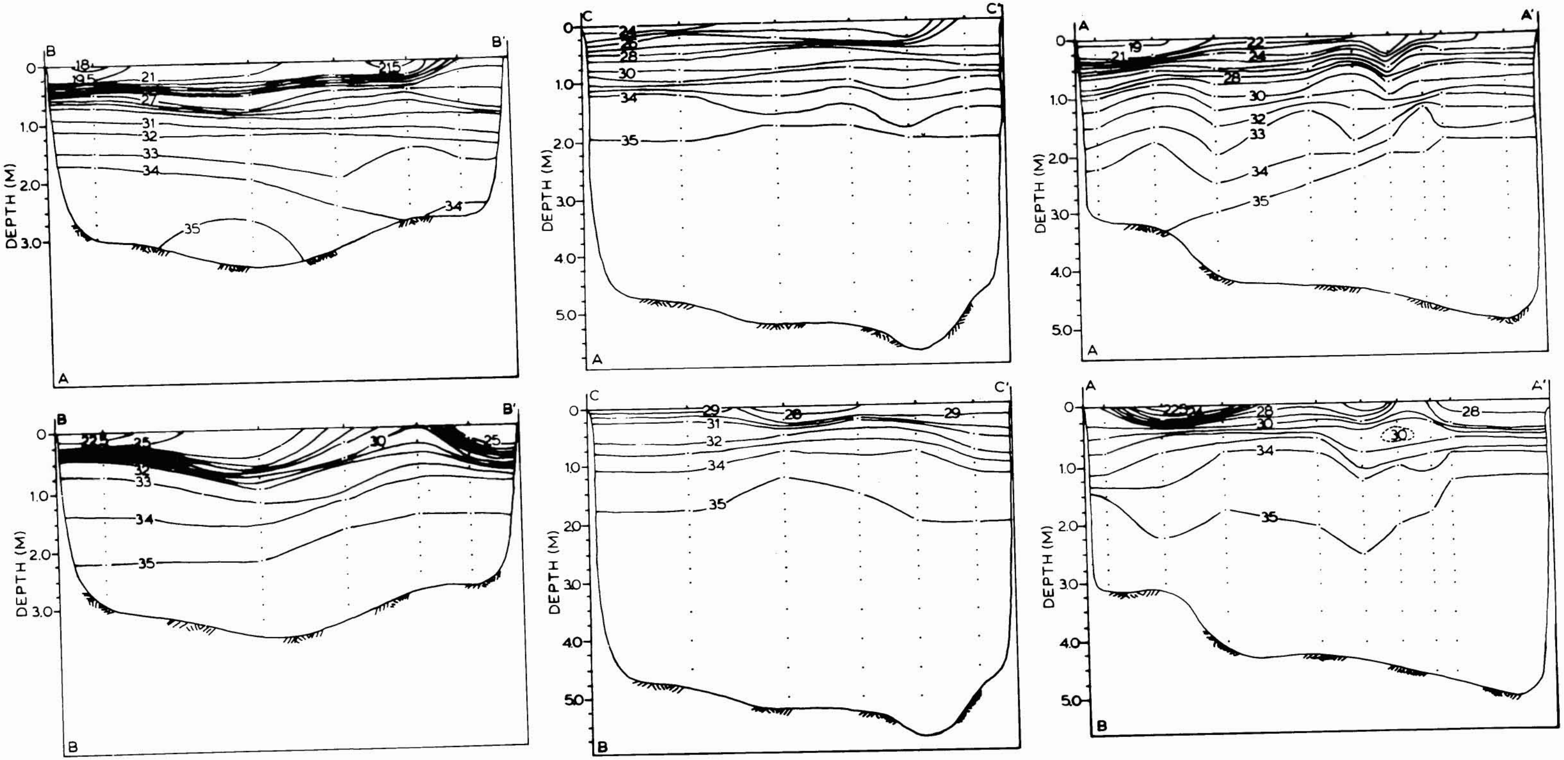

FIGURE 3. Cross sections showing vertical profiles of salinity in Honokohau Harbor. Axes A–A′, B–B′, and C–C′ describe transects shown in Figure 1. Figures labeled A and B present conditions at low and high tide, respectively.

berthing basins and analyzed for oxygen content via titration. Dissolved oxygen levels in the back berthing basin were 4.53 ml O_2/liter in the surface waters and 5.83 ml O_2/liter in the waters near the bottom. The slightly lower values at the surface may reflect the recent introduction of groundwater that was previously out of contact with the atmosphere. In the front berthing basin, which does not directly receive large quantities of brackish water input, the dissolved oxygen measured 5.44 ml O_2/liter at the surface and 5.18 ml O_2/liter in the subsurface layer. The surface layer in the front basin is maintained by the brackish inputs originating in the back basin. The higher oxygen levels in these waters, relative to those of the back basin, results from equilibration with the atmosphere as this layer flows seaward. Oxygen levels in both areas and depths are near saturation concentrations for the existing temperature and salinity conditions.

Turbidity

Turbidity was measured simultaneously at all stations and depths with temperature and salinity. The results (not presented here) indicate that low turbidity conditions prevail in the harbor as a whole; transmisometer values were nearly always higher than 90 percent transmittance over the 20-cm light path. Earlier studies (Oceanic Institute 1975*a*) conducted with a turbidometer show intraharbor turbidity levels less than or equal to 0.50 FTU (Fluorescence Turbidity Units) compared with values less than or equal to 0.20 FTU outside the harbor. High correlation ($p = 0.01$) of turbidity and chlorophyll data show that most of the turbidity is due to phytoplankton biomass. The dominantly biological turbidity components account for water clarity decline throughout the day. Turbidity shows nonsystematic variation with both depth and location within the harbor. It is interesting to note that turbidity does not show a tendency to increase in the back reaches of the harbor at either high or low tide, indicating the adequacy of flushing processes in maintaining water clarity.

Hydrology

Figure 1 shows the location of the dominant groundwater inputs. On the basis of our observations, there appear to be two types of input: a general percolation type of inflow through the harbor walls and a more rapid flow type of input originating from a distinct location in the harbor floor. Both types of input are most prevalent in the back berthing basin. Within this basin most of the inflow occurs along the northern end. Two discrete sources of input also occur along the eastern and southern sides. The influx of groundwater is of sufficient magnitude to cause a persistent outflow of surface water from the harbor, regardless of the tidal cycle.

Analysis of the chemical and physical data indicates that the incoming groundwater has the following properties: temperature $\approx$ 21°C, salinity $\leq$ 21‰, nitrate $\approx$ 35.7 µg-atom/liter, phosphate $\approx$ 2.4 µg-atom/liter, N/P ratio $\approx$ 15, overall influx rate of about 71 m^3/min.

Water Chemistry

The pH of the waters within Honokohau Harbor ranged from 8.02 to 8.21. Lowest values were generally found in the upper 0.5 m within the brackish layer, and pH values were highest in the 3.0-m samples. Coastal waters adjacent to the harbor showed similar values as the subsurface waters within the harbor and averaged 8.18 $\pm$ 0.03. Total alkalinity values showed a similar trend. Values were lowest in the 0.5-m samples (1.79 $\pm$ 0.08 m equiv/liter) and increased with depth to maximum recorded levels at 30 m (2.24 $\pm$ 0.04 m equiv/liter). Carbonate alkalinity ranged from 1.73 $\pm$ 0.09 m equiv/liter at the surface to 2.14 $\pm$ 0.03 m equiv/liter at 3.0 m.

The concentrations of nitrate (NO_3^-) at various locations within Honokohau Harbor and adjacent coastal waters are listed in Table 1. The outstanding feature of these values, which range from 0.40 to 33.66 µg-atom/liter, is the high nitrate content of the surface waters within the harbor. Similar distributions of nitrate were also found in previous investigations and are related to the

TABLE 1

NUTRIENT CONCENTRATIONS AT SELECTED STATIONS WITHIN HONOKOHAU HARBOR

		EBBING TIDE CONDITIONS			FLOODING TIDE CONDITION		
STATION	DEPTH (m)	NITRATE	PHOSPHATE	AMMONIUM	NITRATE	PHOSPHATE	AMMONIUM
1	0.5	27.27 ± 3.90	1.96 ± 0.04	1.34 ± 0.94	33.66 ± 3.20	2.50 ± 0.28	0.55 ± 0.05
	1.5	9.64 ± 1.24	0.62 ± 0.13	0.42 ± 0.12	8.23 ± 1.15	0.63 ± 0.06	0.69 ± 0.34
	3	3.80 ± 1.69	0.32 ± 0.10	0.58 ± 0.35	3.85 ± 1.20	0.39 ± 0.02	0.28 ± 0.05
2	1.5	6.58 ± 1.11	0.50 ± 0.04	0.50 ± 0.24	11.48 ± 0.69	0.77 ± 0.05	0.25 ± 0.07
	3	1.43 ± 0.15	0.31 ± 0.02	0.80 ± 0.18	1.46 ± 0.29	0.27 ± 0.03	0.31 ± 0.14
3	0.5	23.52 ± 0.54	1.76 ± 0.06	1.21 ± 0.88	23.02 ± 4.44	1.58 ± 0.07	0.54 ± 0.11
	1.5	4.42 ± 1.37	0.45 ±0.18	0.92 ± 0.71	7.70 ± 5.50	0.75 ± 0.49	0.23 ± 0.12
	3	0.48 ± 0.19	0.21 ± 0.02	0.92 ± 0.94	1.28 ± 0.25	0.32 ± 0.17	0.61 ± 0.22
4	1.5	3.39 ± 2.96	0.46 ± 0.24	0.46 ± 0.18	5.20 ± 0.98	0.49 ± 0.05	0.29 ± 0.11
	3	0.60 ± 0.28	0.27 ± 0.10	0.75 ± 0.71	0.40 ± 0.15	0.20 ± 0.03	0.27 ± 0.04
5	1.5	0.58 ± 0.06	0.26 ± 0.04	0.21 ± 0.06	0.70 ± 0.63	0.19 ± 0.02	0.15 ± 0.19
	5	0.19 ± 0.07	0.22 ± 0.05	0.63 ± 0.53	0.31 ± 0.19	0.14 ± 0.02	0.25 ± 0.00

NOTE: Values are listed in units of μg-atom/liter and represent the mean (±SD) of duplicate analyses on each of two separate samplings.

influx of brackish groundwater through the walls and floor of the harbor, predominantly in the innermost berthing basin represented by station 1. The resulting configuration of nutrient-rich, low-density, brackish water lying on top of nutrient-poor, higher-density seawater accounts for the distribution of nitrate and phosphate within the harbor.

Actual sample collection varied somewhat from day to day, and resulting proximity to point sources of brackish water inputs (Figure 2) accounts for the majority of variation shown at a given station. Concentrations at 1.5 and 3.0 m show a systematic decline of nitrate from high values at station 1, in the back reaches of the harbor, through stations 2, 3, 4, and finally to ambient levels at station 5 outside the harbor. Nitrate at 3.0 m at station 4 was not significantly different from 1.5-m levels at station 5. The concentration of nitrate at station 5 always showed that 1.5-m values exceeded 5.0-m values, although the magnitude of change was considerably less than that observed in the harbor itself. Drogue studies and other physical measurements showed that the direction of the harbor effluent, which occurs at all times regardless of the tidal cycle, was west in the direction of station 5. Previous data (Oceanic Institute 1975*a*) suggest that the surface nitrate concentration at station 5 is comparable to the 1.5-m nitrate levels at station 5. Comparison of nitrate levels for stations 4 and 5 illustrates the magnitude of mixing and dilution occurring over this approximately 150-m distance.

There is apparent variation of ambient nitrate in response to the prevailing tidal conditions. Nitrate concentrations at station 1 were about 6.3 μg-atom/liter higher under low tide conditions than under higher tide conditions. This undoubtedly results from mixing and correspondingly greater relative contributions of brackish water inputs to the harbor waters at low tide. This general trend was apparent at stations 2, 3, 4, and 5—particularly at 1.5 m.

Data from previous years' investigations demonstrate considerable annual variation in nitrate levels, apparently related to incident rainfall. Mean values from the 1971, 1972, 1973, and 1974 surveys showed nitrate concentrations at station 1 to be 30.63, 39.71, 21.55, and 30.47 μg-atom/liter, respectively. Similar variations were evident for other stations. Comparing the levels over the 4-year period, the highest nitrate recorded was 43.9 μg-atom/liter.

Nitrite (NO_2^-) analyses were performed in the 1975 reconnaissance, and levels were found to be low or undetectable in all cases. The 1971 survey reported levels of 10^{-2} μg-atom

NO_2^-/liter overall, and there appeared to be no systematic vertical or spatial distribution characteristics. This shows that the nitrogen contained in the brackish water is represented mainly by nitrate.

The concentration of phosphate (PO_4^{3-}) at various locations within Honokohau Harbor and adjacent waters is also given in Table 1. Similar to the nitrate results, the outstanding feature of the phosphate data is the high surface values. Phosphate concentrations range from 0.14 μg-atom/liter in the subsurface waters at station 5 to 2.50 μg-atom/liter in the surface waters at station 1 under low tide conditions. The phosphate levels in the subsurface waters do not differ significantly from normal ambient concentrations expected in coastal areas. The surface values are roughly an order of magnitude less than corresponding nitrate values; this typical relationship of nitrogen–phosphorus concentrations is a result of the natural groundwater processes. The vertical distribution shows that phosphate is highest in the surface waters, represented by the 0.5-m samples. Previous studies have shown that the high phosphate surface concentrations at stations 1 and 3 are also found in other provinces of the harbor. Phosphate levels at 1.5 m are about 25–45 percent of the corresponding surface values, and for all 3.0-m samples, except station 1, phosphate is very close to ambient levels in the adjacent coastal waters. Intermediate phosphate levels at 1.5 m probably result from vertical mixing between the high-phosphate brackish water and the low-phosphate seawater layer. Horizontal variation in phosphate levels was much less pronounced than vertical variation. Station 1 values at the surface tend to be greater than station 3 values, reflecting the proximity of groundwater inputs. A general trend of decreasing phosphate levels at locations more distant from the back provinces of the harbor seems to apply to data representating all depth and tidal conditions.

Phosphate levels respond to the tidal conditions in much the same manner as do nitrate levels, phosphate being highest when the tide is low. This trend is most apparent in the back berthing area (station 1), which receives the groundwater inputs. No such tidal variation in phosphate is evident at the oceanic control station (5) outside the harbor. This tidal response of phosphate and nitrate points to the fact that hydraulic rather than biological processes predominate in affecting the ambient levels of these nutrients, particularly in the surface waters.

Comparison of the phosphate at 3.0 m at station 4 with the levels at station 5 suggests that below 3.0 m, the water within the harbor is essentially oceanic in nutrient character. At 2.5 m, the phosphate concentration is essentially that of the adjacent coastal waters, and at 3.5 m, the phosphate is as low as the mean phosphate at 5.0 m at station 5. Supplementary data from previous surveys show considerable variation in ambient phosphate as was apparent for nitrate. Data from 1971–1973 show the range of variation at station 1 (0.5 m) to be 0.96–3.15 μg-atom/liter, with corresponding variations for other stations. The highest phosphate level recorded (3.23 μg-atom/liter) occurred in 1972 and corresponded to conditions of increased rainfall.

The concentration values of ammonium within the harbor and in adjacent waters (Table 1) show that the distribution of ammonium nitrogen does not follow the trend described for nitrate and phosphate. Values in the surface waters show less enhancement relative to subsurface waters, suggesting that ammonium (a reduced nitrogenous radical) is not present in the groundwater to any great extent. Further comparison of ammonium data for previous surveys shows similar concentrations in space and time and no dependence on rainfall conditions. The range of ammonium figures, 0.15–1.34 μg-atom NH_4^+/liter, is not distinctly different from what might be encountered in a coastal system. No clear vertical, spatial, or tidal variations in the ambient concentration of ammonium are apparent. Ammonium levels within the harbor, though showing isolated high values (1–2 μg-atom/liter), were not distinctly different from levels outside the harbor.

In contrast to the situation for nitrate and phosphate, biological rather than hydraulic processes are probably responsible for controlling ammonium levels within the harbor. The grazing and excretion activities of zooplankton probably account to a large extent for the production of ammonium, and these processes are balanced by the rapid assimilation of NH_4^+ by phytoplankton. The suggestion in Table 1 that ammonium was higher at falling tide conditions may be an artifact of the analysis; higher figures given for stations 1 and 3 at 0.5 m were influenced by a single high value in each case.

Water samples were analyzed to determine whether the harbor waters, by virtue of either boating activities or groundwater intrusion, showed evidence of enhanced heavy metal concentrations that might adversely affect the aquatic communities. The concentrations of 17 metals were determined in samples taken from the surface waters of the back basin and from the oligotrophic coastal waters outside the harbor. Results showed no evidence of elevated heavy metal levels within the harbor. Thirteen of the metals were undetectable at the concentration (μg/liter) in parentheses: (10^{-3}) Sb, Co, Cr, Hg, Ag; (10^{-2}) Cd, Pb, Mn, Sn, Zn; (10^{-1}) As, Ti, V. The metals Ni, Mo, and Cu showed similar levels (10^{-3} μg/liter) at the two locations, and Fe levels were 1.4×10^{-2} μg/liter within the harbor and 1×10^{-2} μg/liter in the adjacent coastal waters.

For the most part, the sediment depth ranges from 1 to 25 cm, but isolated areas as thick as 70 cm also exist. The floor of both the entrance and the interconnecting channels showed a very thin sediment cover (≤ 5 cm). On the floor of the back basin, rocky outcroppings predominate. Isolated sediment pockets about 10 cm deep exist between the rocks, but these pockets constitute less than 10 percent of the center area. There is slightly more sediment along the northern wall of the back basin than exists along the other walls, and this may be related to the increased amounts of groundwater entering this area. Sediment thickness in the deeper front basin was similar to that in the back basin with the exception of generally higher values in the southerly end. Sediments are black pumice throughout the harbor and appear to be residues of ground lava rock, possibly the result of blasting activities that created the harbor and/or the grazing activity of the prolific echinoid populations in the harbor. The percentage of organic matter contained within the harbor sediments ranged from 0.79 to 2.81 percent, and values showed no distribution trends. Particle size analysis of the sediment samples (Oceanic Institute 1975*b*) was by dry sieve analysis. The 20 sediment samples inspected for size analysis showed that throughout the harbor, most of the sediment (about 90 percent) was composed of fine sand to silt-size fractions.

DISCUSSION

The observed distributions of temperature, salinity, and nutrients in the Honokohau Harbor environment result from the persistent influx of groundwater to the back reaches of the harbor. The greatest groundwater reservoir for the area and the entire island lies near sea level, where freshwater recharge from rainfall accumulates in widespread bodies floating on the slightly heavier seawater. The interface of this dynamic Ghyben–Herzberg system, which may be brackish up to several miles inland (Davis and Yamanaga 1968), results from the mixing of freshwater and seawater (Wentworth 1942, Swain 1973). Movement is continuous within this subterranean water body as freshwater recharge percolates into the lens at the water table and moves laterally to the sea. The water table gradient in the Honokohau area is about 1 ft/mi seaward (Department of Land and Natural Resources 1968). Continuous freshwater addition via rainfall infiltration and movement down the slopes toward the shore necessitates a means of outflow. Most of this groundwater escapes into the sea as diffused flows along the shore, and at a few places it is concentrated in large springs (Fisher et al. 1966). The groundwater influx in the Honokohau area is comparatively low because of the small recharge resulting from low rainfall and high evapotranspiration conditions of

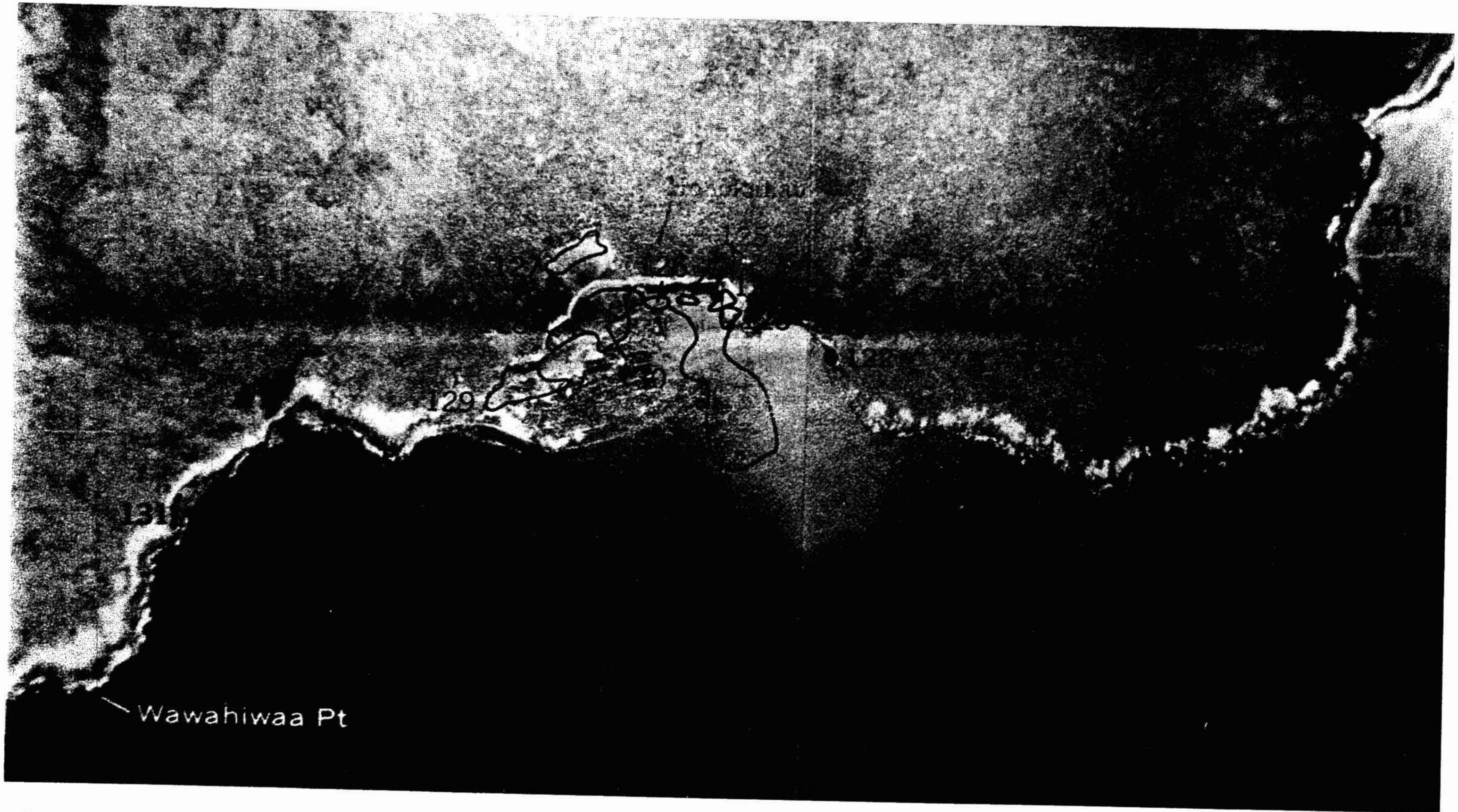

FIGURE 4. Infrared photograph showing natural groundwater intrusion in the area prior to creation of Honokohau Harbor.

the area (Cox et al. 1969). Recharge in the wet zones on the west Hualalai slopes probably accounts for most of the recharge and amounts to several tens of millions of gallons per day (Davis and Yamanaga 1968). Brackish water discharge in the Honokohau shoreline area has been estimated to be a few million gallons per day per mile (Cox et al. 1969). Figure 4 is an infrared image depicting thermal anomalies resulting from cold groundwater discharge in the area prior to the creation of the harbor. The photograph shows that the harbor site was a location of natural, prolific groundwater discharge. Excavation of the harbor has displaced the natural discharge points in the immediate area landward. This landward displacement of the discharge interface may also have caused enhanced discharge in the area by affecting the gravity-flow path of subterranean water movement and directing it toward the point of easiest discharge. The oceanographic analysis suggests that 1.5–2 mgd of groundwater discharge into the present harbor. This influx occurs at sufficient rates to produce a continual outflow at the surface, irrespective of the direction of tidal flow. Location of the predominant inputs at the back reaches of the harbor results in surface outflow of the entire basin. This process also entrains subsurface waters and thereby reduces the effects of molecular diffusion of surface nutrients to the subsurface ocean water and enhances harbor flushing rates. The flushing rates of the harbor are over six times larger than would be produced solely by tidal action.

High nutrient concentrations of the harbor surface waters and the close correlation with thermohaline parameters indicate that groundwater is the major contributor of nitrate and phosphate throughout the harbor. Nutrient analyses of groundwater samples, collected at the immediate origin into the harbor over the years, showed insignificant different levels, suggesting that annual variations in the surface harbor water chemistry are attributable to differing discharge rates and/or mixing rather than to fluctuations in nutrient concentrations within the groundwater. It is interesting to note that the high nutrient levels in the groundwater, which result from leaching, appear in a ratio of $N/P = 15$, similar to the ratio in deep ocean waters where high nutrient levels are maintained by regeneration of biological material. Low levels of nitrite and ammonium in the surface water suggest that nitrogen is not represented by reduced nitrogenous radicals in uncontaminated groundwater to an appreciable degree.

This detailed study of Honokohau Harbor dramatizes the potential influence of the hydrological character of a particular locality upon the water quality of a coastal embayment. Recognition of the potential impact of groundwater nutrients on similar coastal developments is an obvious feature of the study. Such a potentially eutrophying phenomenon could markedly affect the aesthetic and water quality character of created island embayments, particularly when the discharge is significant and/or tidal flushing is not extensive. The study suggests that consideration of land slope and rainfall, which would have suggested low groundwater discharge rates in the Honokohau area, cannot be used to predict the likelihood or extent of groundwater effects. The fact that the benign effects of this nutrient influx are maintained by rapid transport rates from the harbor suggests that design of coastal developments consider harbor size, flushing, and mixing rates as critical criteria in maintaining high water quality both within harbors and in the adjacent coastal waters.

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